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II.

APPENDIX TO PAPER ON THE MECHANICAL EQUIVALENT OF HEAT, CONTAINING THE COMPARISON WITH DR. JOULE'S THERMOMETER.

By H. A. ROWLAND.

Presented, March, 1880.

In the body of this paper I have given an estimate of the departure of Dr. Joule's thermometer from the air thermometer, based on the comparison of thermometers of similar glass. But as it seemed important that the classical determinations of this physicist should be reduced to some exact standard, I took to England with me last summer one of my standards, — Baudin, No. 6166, — and sent it to Dr. Joule with a statement of the circumstances. He very kindly consented to make the comparison, and I now have the results before me. These confirm the estimate that I had previously made, and cause our values for the equivalent to agree with great accuracy. The following is the table of the comparison.

Readings.		Temperatures.		
Baudin, No. 6166.	Joule.	By perfect Air Thermometer according to No. 6166.	By Joule's Thermometer.	Difference.
21.88	22.62	0	0	0
41.930	59.410	1.590	1.578	— .012
48.782	72.200	2.126	2.127	+ .001
53.705	81.340	2.511	2.519	.008
58.916	90.877	2.918	2.928	.010
64.914	101.777	3.382	3.396	.014
73.374	117.291	4.039	4.061	.022
80.176	129.990	4.567	4.606	.039
85.268	139.255	4.961	5.003	.042
90.564	148.834	5.370	5.414	.044
94.243	155.460	5.654	5.698	.044
99.168	164.400	6.036	6.082	.046

Readings.		Temperatures.		
Baudin, No. 6166.	Joule.	By perfect Air Thermometer according to No. 6166.	By Joule's Thermometer.	Difference.
104.080	173.140	6.413	6.457	.044
108.863	182.040	6.789	6.839	.050
113.706	190.885	7.165	7.218	.053
114.000	191.382	7.188	7.239	.051
*121.507	*219.497	*7.772	*8.445	...
135.858	231.115	8.890	8.944	.054
140.467	239.939	9.249	9.309	.060
143.405	245.006	9.479	9.540	.061
146.445	250.566	9.717	9.778	.061
152.360	261.481	10.180	10.246	.066
158.770	273.239	10.681	10.751	.070
164.635	283.957	11.138	11.211	.073
170.485	294.739	11.595	11.670	.075
175.436	303.682	11.979	12.057	.078
182.795	316.968	12.550	12.627	.077
188.705	327.746	13.008	13.089	.081
193.954	337.220	13.412	13.495	.083
199.558	347.294	13.844	13.928	.084
206.054	259.060	14.343	14.432	.089
211.528	368.953	14.764	14.857	.093
216.440	377.826	15.142	15.237	.095
221.858	387.562	15.560	15.655	.095
229.601	401.419	16.158	16.249	.091
235.598	412.367	16.623	16.719	.096
241.028	422.258	17.045	17.143	.098
247.436	433.800	17.541	17.638	.097
253.704	445.267	18.028	18.130	.102
259.786	456.286	18.500	18.603	.103
266.086	467.817	19.991	19.097	.106
273.143	480.643	19.539	19.648	.109
280.176	493.442	20.086	20.197	.111
287.634	506.906	20.666	20.774	.108
294.927	520.052	21.232	21.338	.106
304.148	536.832	21.947	22.058	.111
310.397	548.152	22.432	22.544	.112
316.596	559.336	22.916	23.023	.107
321.271	568.051	23.282	23.397	.115
327.148	578.528	23.742	23.846	.104
333.661	590.661	24.251	24.367	.116
339.664	601.596	24.719	24.836	.117
346.557	614.004	25.254	25.369	.115
352.878	625.510	25.746	25.862	.116
359.986	638.526	26.299	26.421	.122
365.080	647.833	26.697	26.820	.123
371.811	660.071	27.225	27.345	.120
382.770	680.149	28.087	28.206	.119

We can discuss the comparison of these thermometers in two ways; either by direct comparison at the points we desire, or by the representation of the differences by a formula.

* Evidently a mistake in the readings.

Joule's result in 1850 was referred to water at about 14° C., and in 1878 to water at $16^{\circ}.5$ C. Taking intervals in the above table of from 6° to 12° , so that the mean shall be nearly 14° and $16^{\circ}.5$, I find the following for the ratios:—

	1.0044	1.0042
	1.0042	1.0042
	1.0049	1.0040
	1.0047	1.0030
	1.0047	1.0035
	1.0052	1.0035
Mean,	<u>1.0047</u>	<u>1.0037</u>

So that we have the following for Joule's old and new values:—

	Old.	New.
	423.9	423.9
Correction for thermometer	2.0	1.6
“ “ latitude	.5	.5
“ “ sp. ht. of copper	.7	
	<u>427.1</u>	<u>426.0</u>
My value	427.7	427.1
Difference	<u>.6</u>	<u>1.1</u>

or 1 in 700 and 1 in 390 respectively.

But the correction found in this way is subject to local irregularities, and it is perhaps better in many respects to get the equation giving the temperature of Joule's thermometer on the air thermometer. Let T be the temperature by Joule's thermometer, and t that by the air thermometer. Then I have found

$$t = 0.002 + 1.00125 T - .00013 \{100 - T\} \{1 - .003(100 + T)\}$$

The factor 1.00125 enters in the formula, probably because the thermometer which Joule used to get the value of the divisions of his thermometer was not of the same kind of glass as his standard. The relative error at any point due to using the mercurial rather than the air thermometer will then be

$$E = 1 - \frac{dt}{dT} = -.00125 + .00000039 \{23300 - 666t + 3t^2\}$$

From this I have constructed the following table.

Temperature.	E.	Approximate Addition to Equivalent as measured on Joule's Thermometer.	
		Metric System.	English System.
0	.0078	3.3	6.0
5	.0066	2.8	5.1
10	.0054	2.3	4.2
15	.0042	1.8	3.2
20	.0031	1.3	2.4
25	.0021	.9	1.6
30	.0011	.5	.8

Corrected in this way we have, —

	Old.	New.
Joule's value	423.9	423.9
Reduction to air thermometer	1.9	1.7
“ latitude of Baltimore	.5	.5
Correction for sp. ht. of copper	.7	
	427.0	426.1
My value	427.7	427.1
Difference	.7	1.0

or 1 in 600 and 1 in 426 respectively.

But it is evident that all the other temperatures used in the experiment must also be corrected, and I have done this in the following manner. The principal other correction required is in the capacity of the calorimeter, and this amounts to considerable in the experiments on mercury and cast-iron, where no water is used. Dr. Joule informs me that the thermometer with which he compared mine was made in 1844, but does not give any mark by which to designate it, although it is evidently the thermometer called “A” by him. I shall commence with the experiments of 1847. The calorimeter was composed of the following substances, whose capacities I recompute according to what in my paper I have considered the most probable specific heats.

	Weight.	Capacity according to Joule.	Most probable Specific Heat.	Most probable Capacity.
Water	77617 grains	77617	1.000	77617
Brass	24800 “	2319	.0900	2232
Copper	11237 “	1056	.0922	1036
Tin	(?)	363	. . .	363
Total capacity		81355		81248

Equivalent found	781.5 at about 59° F.
Correction for thermometer	3.3
“ “ capacity	1.3
“ “ latitude	.9
Corrected value	<u>787.0</u>

or 442.8 at 15° C. on the air thermometer.

The other experiment, on sperm oil, made at this time, is probably hardly worth reducing. The experiments of 1850 are of the highest importance, and should be accurately reduced.

In the experiments with water the capacity of the calorimeter is corrected as follows:—

	Weight.	Capacity used by Joule.	Most probable Specific Heat.	Most probable Capacity.
Water	93229.7	93229.7	1.000	93229.7
Copper	25541.	2430.2	.092	2349.8
Brass	18901.	1800.0	.091	1720.0
Brass stopper		10.3	. . .	10.3
Total capacity		<u>97470.2</u>		<u>97309.8</u>

Therefore correction is .0016.

Hence the result with water requires the following corrections:—

Joule's value	772.7 at 14° C.
Correction for thermometer	3.2
“ “ latitude	.9
“ “ capacity	1.2
	<u>778.0</u>

or 426.8 on the air thermometer in the latitude of Baltimore at the temperature of 14° C., nearly.

In the next experiment, with mercury, Joule determined the capacity of the apparatus by experiment. The mean of the experiments was that the apparatus lost 20°.33155 F. in heating 143430 grains of water 3°.13305 F. To reduce these to the air thermometer we must divide respectively by 1.0042 and 1.0056. Therefore the capacity must be divided by 1.0014. Therefore the corrected values are:—

	772.8 at 9° C.	775.4 at 11° C.
Correction for thermometer	4.4	4.0
“ “ capacity	1.1	1.1
“ “ latitude	.9	.9
	<u>779.2</u>	<u>781.4</u>

The reduction to the air thermometer was made for the temperatures of 9° C. and 11° C. respectively, but they both refer to the temperature of the water used when the capacity was determined; this was about 9° C. Hence these experiments gave 427.5 and 428.7 on the air thermometer, with the water at about 9° C.

The next experiments, with cast-iron, can be corrected in the same manner, and thus become

	776.0	773.9
Correction for thermometer	4.2	4.3
“ “ capacity	1.1	1.1
“ “ latitude	.9	.9
	<u>782.2</u>	<u>780.2</u>

and these are as before for water at 9° .

The determination by the heating of a wire, whose resistance was measured in ohms, can be thus reduced. The value found by Joule was 429.9 in the latitude of Baltimore at $18^{\circ}.6$ C.

Using the capacity of the copper .0922, as I have done in my paper, this quantity will be increased to 430.3. But I have given reasons in my paper on the “Absolute Unit of Electrical Resistance” to show that there should be a correction to the B. A. Committee’s experiments, which would make the ohm .993 earth quadrant $\div$ second, instead of 1.000 as it was meant to be, which nearly agrees with the quantity which I found, namely, .991. Taking my value .9911, Joule’s result will reduce as follows:—

	429.9 at $18^{\circ}.6$ C.
Correction for thermometer	+ 1.5
“ “ capacity	+ .4
“ “ ohm	— 3.8
Corrected value	<u>428.0 at $18^{\circ}.6$ C.</u>

The last determinations in the “Philosophical Transactions” of 1878 can be reduced as follows.

The capacity of the calorimeter was determined by experiment, instead of calculated from the specific heat of copper given by Regnault, as in the older experiments. The value used, 4842.4 grains, corresponded to a specific heat of brass of about .090, which is almost exactly what I have considered right. The reduction to the air thermometer will decrease it somewhat, and the correction for the increase of the specific heat of brass and the decrease of the specific heat of water will also change it somewhat. In all, the amount will be about 1 in 200. Hence the reduction becomes as follows:—

Joule's values	772.7	774.6	773.1	767.0	774.0
Correction for thermometer	3.2	3.7	3.1	3.3	2.8
“ “ capacity	.2	.2	.2	.2	.2
“ “ latitude	.9	.9	.9	.9	.9
“ to vacuum	— .9	— .9	— .9	— .9	— .9
Corrected values	776.1	778.5	776.4	770.5	777.0
	at 14°.7	at 12°.7	at 12°.5	at 14°.5	at 17°.3

To reduce the values in English measure to meters and the Centigrade scale, I have simply taken the reducing factor $1.8 \times .304794$, although the barometer on the two systems is not exactly the same: for this is taken into account in the comparison of the thermometers. However, a barometer at 30 in. and 60° F. is equivalent to 759.86 mm. at 0° C. which hardly makes a difference of 0°.01 C. in the temperature of the hundred-degree point.

No.	Date.	Method.	Tem. of water.	Joule's Value.	Joule's Value re- duced to Air Ther- mometer and Lat- itude of Baltimore.		Rowland's Value.	J. — R.	Estimated weight.
					English measure.	Metric system.			
1	1847	Friction of water	15°	781.5	787.0	442.8	427.4	+15.4	0
2	1850	“ water	14	772.7	778.0	426.8	427.7	— .9	10
3	“	“ mercury	9	772.8	779.2	427.5	428.8	— 1.3	2
4	“	“ mercury	9	775.4	781.4	428.7	428.8	— .1	2
5	“	“ iron	9	776.0	782.2	429.1	428.8	+ .3	1
6	“	“ iron	9	773.9	780.2	428.0	428.8	— .8	1
7	1867	Electric heating	18.6			428.0	426.7	+ 1.3	3
8	1878	Friction of water	14.7	772.7	776.1	425.8	427.6	— 1.8	2
9	“	“ “	12.7	774.6	778.5	427.1	428.0	— .9	3
10	“	“ “	15.5	773.1	776.4	426.0	427.3	— 1.3	5
11	“	“ “	14.5	767.0	770.5	422.7	427.5	— 4.8	1
12	“	“ “	17.3	774.0	777.0	426.3	426.9	— .6	1

In combining these so as to get at the true difference of Joule's and my result, we must give these different determinations weights according to their respective accuracy, especially as some of the results, as No. 11, have very little weight. Joule rejected quite a number of his results, but I have thought it best to include them, giving them small weights, however. In this way we obtain a value for Joule's experiment of 426.75 at 14°.6, my value at this point being 427.52. The difference amounts to 1 in 550 only. Giving the observations equal weights, this would have been 1 in 430 nearly. The quantity 426.75 is what I find at 18° C. So that my result at this particular temperature differs from that of Joule only the amount that water changes in specific heat in 3°.4 C.

Joule's value is *less* than my value to the amount given, but the value from the properties of air, 430.7 at 14° C. is greater, although the method can have little weight.

It might be well to diminish my values by 1 part in 1000 so as to make them represent the mean of Joule's and my own experiments. It is seen that the experiment by the method of electric heating agrees very exactly with the other experiments, *because I have reduced it to my value of the ohm*. Hence I regard it as a very excellent confirmation of my value of that unit.

BALTIMORE, Feb. 16, 1880.